REPORT DOCUMENTATION

AD-A255 406

Form Approved
OMB No. 0704-0188

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1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE 12-15 June 1990

3. REPORT TYPE AND DATES COVERED Scientific Paper

4. TITLE AND SUBTITLE
Hyperspectral Imagery - A New Technique for Targeting and Intelligence

5. FUNDING NUMBERS

6. AUTHOR(S)
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8. PERFORMING ORGANIZATION REPORT NUMBER
R-184

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

DTIC
ELECTE
SEP 01 1992
S B D

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release;
Distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
Because all materials reflect, absorb, or emit photons in ways characteristic of their molecular makeup, a high-resolution trace of the intensity of the transmitted, reflected, emitted, or luminesced radiation versus wavelength forms a graphical record unique to a given material. The laboratory use of spectral measurements to identify minerals, pigments, and organic and inorganic compounds is an established and reliable technique; and, the reasoning goes, if such could be done from air or space, it would give remote sensing a similar capability. Unfortunately, the useful absorption bands are narrow, 10 nm or less, and cannot be recorded with broad band systems such as Landsat. With the advent of the Airborne Visible Infrared Imaging Spectrometer (AVIRIS) and similar systems, the narrow band capability entered the remote sensing domain. AVIRIS is a true spectrometer, collecting reflected solar energy (0.4-2.5 micra) in about 220 channels, or images, each in a spectral bandwidth of about 9.6 nm. This type of narrow band information is called hyperspectral.

14. SUBJECT TERMS
1. Hyperspectral Imagery
2. Landsat
3. Intelligence
4. Remote Sensing

15. NUMBER OF PAGES 16

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	

NSN 7540-01-280-5500

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298-102

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Presented at the Army Science Conference, 12-15 June 1990, Durham, NC.

TITLE: Hyperspectral Imagery - A New Technique for Targeting and Intelligence

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ABSTRACT: Because all materials reflect, absorb, or emit photons in ways characteristic of their molecular makeup, a high-resolution trace of the intensity of the transmitted, reflected, emitted, or luminesced radiation versus wavelength forms a graphical record unique to a given material. The laboratory use of spectral measurements to identify minerals, pigments, and organic and inorganic compounds is an established and reliable technique; and, the reasoning goes, if such could be done from air or space, it would give remote sensing a similar capability. Unfortunately, the useful absorption bands are narrow, 10 nm or less, and cannot be recorded with broad band systems such as Landsat. With the advent of the Airborne Visible Infrared Imaging Spectrometer (AVIRIS) and similar systems, the narrow band capability entered the remote sensing domain. AVIRIS is a true spectrometer, collecting reflected solar energy (0.4-2.5 micra) in about 220 channels, or images, each in a spectral bandwidth of about 9.6 nm. This type of narrow band information is called hyperspectral. For any ground spot in the image, one can call up a plot of intensity of the 220 bands, i.e., an intensity versus wavelength for the 0.4-2.5 micra wavelength range. In support of using hyperspectral systems for targeting, the U.S. Army Engineer Topographic Laboratories has developed a series of spectral reflectance, luminescence, and thermal infrared data bases of field and laboratory measurements of some 1,000 samples of soils, rocks, vegetation, and foreign and domestic camouflage materials. No technique is a panacea, and the hyperspectral systems are no exception; but, from the standpoint of targeting, they have potential beyond any previous remote sensor. Because of the broad applicability of such data bases and techniques to military and civil needs, this effort has been expanded into a cooperative interagency effort involving the U.S. Geological Survey and the U.S. Department of Agriculture, among others.

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DEGREES HELD: B.S., 1947; M.S., 1950; Ph.D, 1957; Purdue University, West Lafayette, Indiana.

Hyperspectral Imagery - A New Technique For Targeting and Intelligence

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Divide and conquer has been the motif of the remote sensing community in its quest for ever more and ever narrower spectral bands to record terrain and target information. Over the years, this has led to an expansion into disparate portions of the electromagnetic spectrum, such as microwave, thermal infrared, photo, and visual, as well as to a contraction of recording bandwidth within any given spectral region. The drive towards narrow bands has been especially successful in the reflected solar radiation portion of the spectrum, i.e., the wavelength range of 0.35-2.5 micra, which represents about 84 percent of the sun's energy.

Why the drive to more and narrower bands? Primarily, by reason of the belief that such will lead to improved detection and identification techniques - a rationale that has much to support it, because the finer the cut of spectral data, the greater the ability to establish identities and conditions.

Because all materials reflect, absorb, or emit photons in ways characteristic of their molecular makeup, a high-resolution trace of the intensity of the transmitted, reflected, emitted, or luminesced radiation versus wavelength forms a graphical record unique to a given material. Different materials cannot have identical spectral wave shapes of reflectance, emittance, and luminescence. These characteristic absorption and emission bands occur in narrow wavelength ranges, 10 nanometers (nm) or less; and, unless the instruments have that kind of spectral resolution, these details cannot be recorded. Although many laboratory and field instruments exceed this spectral resolution, airborne systems have only recently entered this domain. Figure 1 shows examples of spectral reflectance measurements and indicates some of the more common absorption bands. From a laboratory point of view, the use of spectral measurements to identify and/or assay components of minerals, pigments, pharmaceutical and other organic and inorganic compounds, is old, established, and reliable. With reference to remote sensing, the reasoning goes that if such could be done from air or space, it would give remote sensing a similar capability.

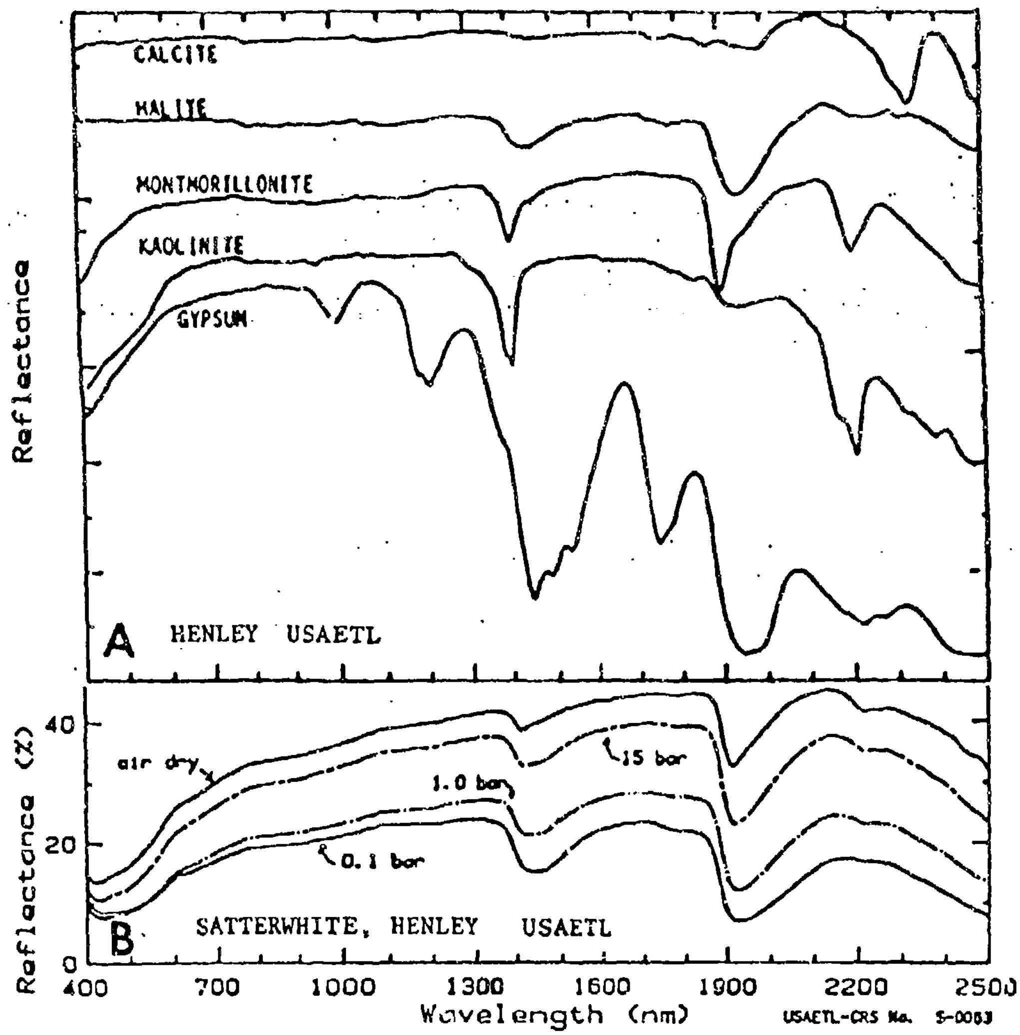

Fig. 1. A. Reflectance measurements of playa surface minerals[1] (records offset vertically to avoid overlap). The strong water absorption bands at 1400 and 1900 nm are apparent. When both are present, it indicates undissociated water, i.e., free water, water of hydration, trapped water in the lattice, etc. Kaolinite shows strong hydroxyl absorption at 1400 and 2200 nm but little at 1900 nm, which suggests a lack of bound water. Molecular water is important in gypsum, and its overtones and combinatorial tones account for the bands at 1000, 1200, and 1700 nm. Calcite is fairly featureless except for the carbonate molecular vibration band at 2300 nm, and sometimes a weak band at 2000 nm. B. Influence of moisture on a silty loam playa soil from Broadwell Lake, San Bernardino, CA, April 1988.[2]

In relation to systems development, the Army, along with other groups in the 1940s and 50s, divided the photographic portion of the electromagnetic spectrum into narrower bandpasses by using various combinations of photo emulsions and filters[3] - i.e., multiband photography. The bandpasses, however, were still broad, ranging from 60 to 100 nm.

Next came the Landsat Multispectral Scanner (MSS), which recorded reflected sunlight in four broad bands, followed by the Thematic Mapper (TM) with six bands in the reflected solar region, and one band in the thermal infrared, with the narrowest band being TM band 3 at 60 nm. Whatever spectral variations occur in the terrain within any of these bands are averaged out to arrive at a digital number (DN) representing the brightness for the whole band. Extensions of the multispectral concept into the thermal infrared region of the spectrum include the Advanced Very High Resolution Radiometer (AVHRR), and the airborne Thermal Infrared Multispectral Scanner (TIMS) developed by Daedalus Enterprises, Inc.

In the early 1980s, a system was produced that greatly altered the concepts of multispectral remote sensing with reflected solar energy, i.e., the Airborne Imaging Spectrometer (AIS) developed by the Jet Propulsion Laboratory (JPL).[4,5,6] It recorded reflected solar energy in some 128 channels, or images, within the 1.2-2.4 micra region of the spectrum and with a spectral bandwidth for each channel of less than 10 nm. The AIS evolved into the Airborne Visible Infrared Imaging System (AVIRIS) with some 220 raw data channels, or images, within the 0.4-2.45 micra portion of the spectrum. Resampling gives 210 spectral bands of radiometrically calibrated data. The instantaneous field of view (IFOV) is 1 milliradian, or about 10 meters at operational altitude. Each image is a record of the intensity of reflected sunlight within a spectral bandwidth of less than 10 nm. After calibrations and corrections have been made, the intensity values of the 210 channels, for any given picture element (pixel), can be called up and displayed in sequence along the wavelength axis, as a spectrophotometric trace, i.e., radiometric intensity versus wavelength. Because of the narrowness and multiplicity of the bands, these systems are called hyperspectral, to differentiate them from the broad band systems, e.g., MSS, TM, SPOT, etc. Since then, other narrow bandpass systems have been developed, e.g., the 12 channel imager by Daedalus Enterprises, Inc., and the 64 channel instrument by Geophysical Environmental Research Corp. Planned satellite follow-ons include the Shuttle Imaging Spectrophotometer Experiment (SISEX), and the High Resolution Imaging Spectrometer (HIRIS). Details of these systems can be found in a proceedings issue of the Society of Photo-Optical Instrumentation Engineers.[7]

Figure 2 portrays the hyperspectral concept. The stack of images, 210 in the case of AVIRIS, forms an image cube. The X and Y axes relate to ground, or pixel location, and the third axis to wavelength. Because of the Army's interest in natural and man-made surfaces, it must be able to

work with diverse remote sensor data, and the wavelength axis of its image cube should extend from the ultraviolet, through the reflected solar, thermal infrared, and microwave regions, out to at least L-band radar at about 23.5 cm wavelength, as shown in the figure. Moreover, the Army must be concerned with all photons - reflected, emitted, and luminesced - and be able to move back and forth along the image cube axis, incorporating, evaluating, and comparing whatever imagery bands and other data are available, such as Digital Terrain Elevation Data (DTED). Once the corrected image files are in the computer, the spectral patterns can be evaluated by placing the cursor on the site of interest and bringing up a record of the DN values of each of the involved channels. As a minimum, these data should be able to be displayed as line spectra, intensity versus wavelength spectra, and, in the case of luminescence, as three-dimensional spectra (intensity, excitation, emittance), and as contour plots. The spectra can be evaluated in a number of ways, either directly, or by comparison to a computer library of spectral data bases and models.

Figure 3 is an image cube display of an AVIRIS image over Moffett Field, California. The wavelength axis extends downward. The number 2 on the cube image indicates that it is a record of reflected sunlight in the second, or the 410-420 nm bandpass (approximately). The stack of thin lines parallel to the image and extending downward like pages of a book, are the edges of the other images, i.e., channels 11, 12, 13,... . The strong variations in the edge intensities are due to atmospheric absorption caused mostly by water vapor and oxygen. The dark zone indicated by the arrow consists of four images taken in the atmospheric water absorption bands at 1.35, 1.38, 1.41, and 1.46 micra. With solid and liquid samples, the four bands merge into one broader band centered at about 1.4 micra. See Figure 1. Atmospheric corrections are needed for many targets. If one is interested in vegetation stress, this involves the depths and shapes of a number of water absorption bands. Because water vapor is a component of the atmosphere, the analyst does not know how much of the depth and shape of those water bands is due to atmospheric absorption, and how much is due to vegetation absorption. If corrections can be made to remove the atmospheric component via available models such as LowTran, then the residuum can be attributed to plant water.

An important benefit of an imaging spectrometer is that it provides image patterns and spectral patterns. For terrain information in terms of material identities and conditions, potential for dust generation, engineering site selection and evaluation, probable locations of ground water, subsurface waste disposal, etc., the manual analysis of stereo imagery is still state-of-the-art. For example, an area can be covered with a vegetative mantle, which is all a spectrometer record will show. The stereo shapes of landform and drainage, however, can reveal that beneath the vegetal mantle rests a thinly interbedded series of limestones and shales dipping gently to the west, and with unstable colluvium on the lower slopes.

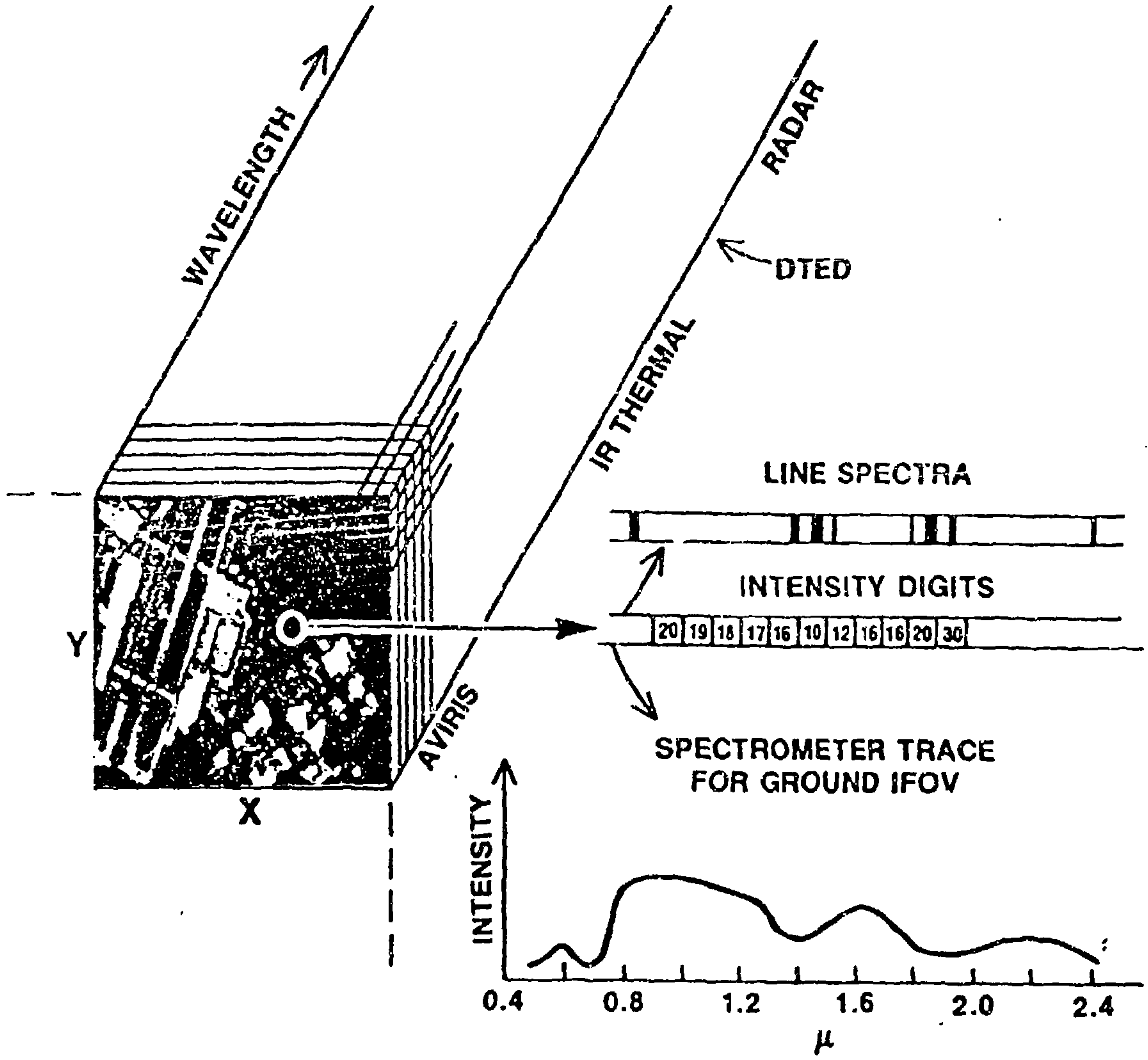

Fig. 2. On the image cube, X and Y indicate ground coordinates, and the third axis is wavelength. For Army purposes it should extend from the ultraviolet out to L-Band radar at 23.5 cm and be able to incorporate other data such as DTED. For any pixel, marked by the cursor, one can sequentially display the intensity values for the bands involved, e.g., MSS, TM, TIMS, AVIRIS, HIRIS, etc., as a line display or as a radiance plot of intensity versus wavelength. These can be compared to computer stored spectral data bases to arrive at probable identities. Or, the scene can be searched for all locations that are a spectral match, within some variance range, for a given spectral signature.

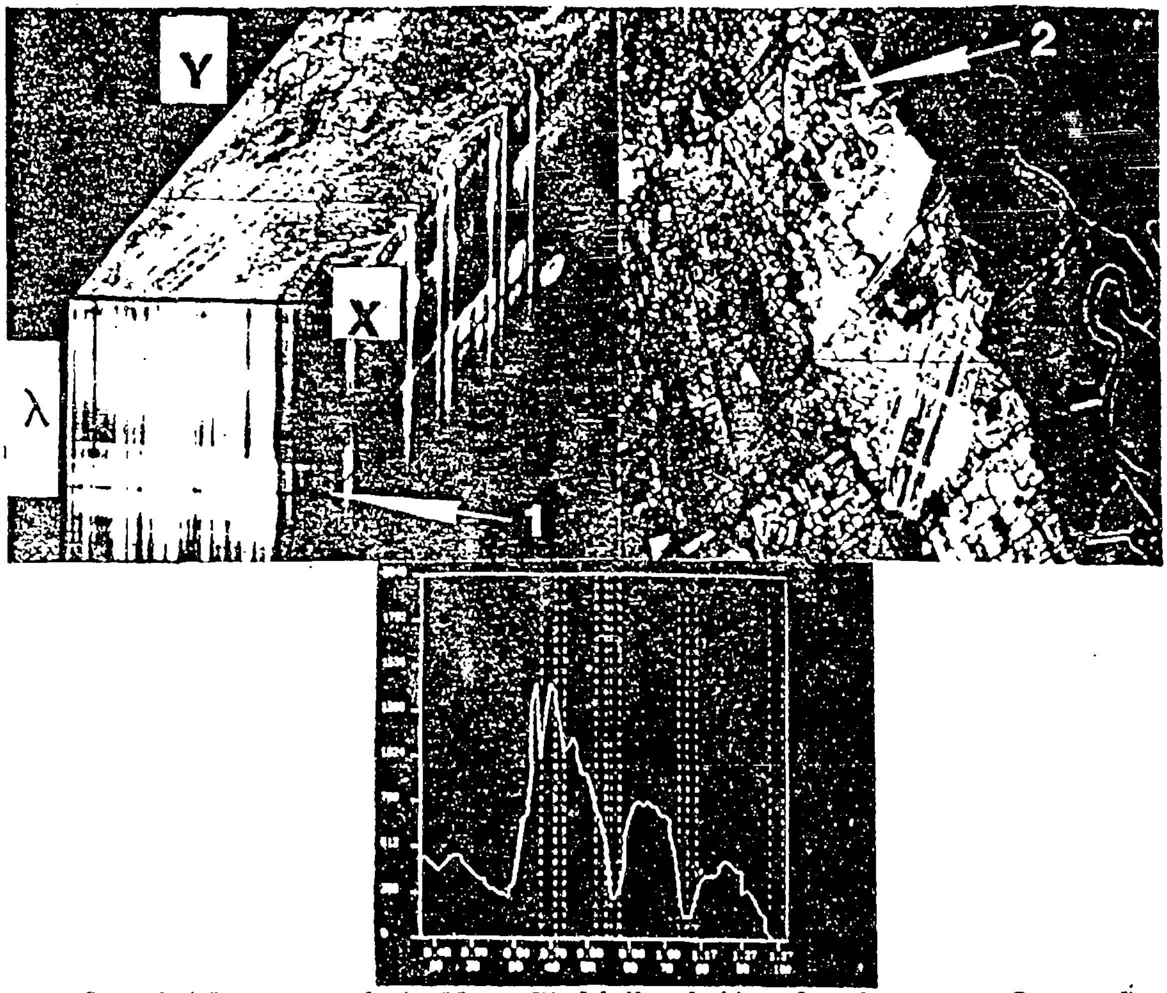

Fig. 3. AVIRIS image of Moffett Field Naval Air Station area, Sunnyvale, CA, taken on 25 June 1987 by JPL. This display was formed on the PIXAR by Barry Holecheck at the U.S. Army Engineer Topographic Laboratories (USAETL). On the image cube the wavelength axis is vertical. The dark zone indicated by arrow no. 1, consists of four images in the water absorption bands at 1.35, 1.38, 1.41, and 1.46 micra. To the right is a black and white print of a color composite image. The graph displays the pixel intensities between 0.4 and 1.37 micra for the vegetated area in the image indicated by arrow no. 2. Although uncorrected for atmospheric absorption, the pattern is typical of chlorophyll. The 12 vertical dashed lines mark atmospheric absorption bands - the left one due to oxygen, and the others due to water vapor. Once corrected, the oxygen band would be eliminated, as well as most traces of the water bands clustered at about .89 and 1.1 micra, and other intensities would be adjusted. The curve would be more similar to plot B at the top of Figure 4.

At present, imaging spectrometers provide only monoscopic imagery, so there is a reduction in the quantity and quality of information that can be derived on the basis of image pattern shapes - but, they are present, and they can make significant direct contributions to an analysis as well as assist in the evaluation of the spectral data. Furthermore, existing routines for combining bands to make color composite images, such as Landsat, Coastal Zone Color Scanner (CZCS), etc., can be applied to AVIRIS imagery as well.

Will this multiplicity of bands lead to data constipation? A good question - and, for the present, the answer is yes, if the data are not properly used. Can the problem be helped by eliminating unneeded bands? Yes, but which ones are unneeded? For targeting minerals, the geologist needs some 30 to 40 bands. For determining crop characteristics, the agriculturalists can get by with perhaps 30 bands, only some of which overlap the geologic needs. The Army, however, with its involvement in terrain use, targeting, cover and concealment, and intelligence, needs information about identities, conditions, and properties associated with vegetation, soils, rocks, minerals, and cultural objects, including camouflage. Doubtless, reductions can be made - but, it is too early for recommendations.

Imaging spectrometer data can be evaluated on the basis of shape of the overall curve, or portions of it, intensity differences/ratios at selected wavelength ranges, wavelength locations of absorption bands, and depths and shapes of absorption bands. To link these to identities requires an extensive library of field and laboratory measurements of spectral reflectance, luminescence, and emittance. Such a library needs excellent documentation, because these measured values change with a variety of factors. For any given surface, the molecular makeup determines the basic characteristics of absorption, reflectance, luminescence, and emittance; but, these are modified by age, weathering, surface structure, orientation, time of day, climate, season, and meteorological variations. For example, vegetation can have smooth, crenulated, or wrinkled leaves of different sizes and arrangements. This means different highlight/shadow ratios, different amounts of transmitted and re-reflected infrared energy through the biomass, and different amounts of radiation reflecting up through the vegetation from the soil surface.[8] For thermal imagery, changes in incoming short and long wave radiation from space, wind, and atmospheric pressure greatly alter signatures and target/background contrasts. Multiplicity of measurements is necessary because there can be significant variation within any given class of targets, especially in field measurements. For current systems and typical target areas, the IFOV (10 meters for AVIRIS) encompasses a mixture of surfaces, and the resulting spectral signature is a composite of individual signatures - i.e., a mixed pixel, which presents another problem in relation to digital analysis of spectral data.

In any event, the airborne imaging spectrophotometric systems are here, and the concepts are sound. The questions are - what are they suited for? - and, how well will they work?

The first example shows why both reflectance and luminescence spectra are needed. Figure 4-A shows the reflectance characteristics of two fabrics, A and C, and of a typical green leaf, curve B. Fabric C is a reasonable match in the visible and out to about 1100 nm. But, it distorts the 1400 nm water absorption band, shows little mimicry of the 1900 nm band, and would be easy to detect, even with TM imagery if it was large enough. Fabric A mimics the vegetation throughout, including the water absorption bands at 1400 and 1900 nm. It would not be detectable against a vegetal background, and would, in fact, be classified as vegetation. Not detectable! Now what? Well, luminescence techniques for one. Although somewhat neglected at present, such have had a number of successful applications, particularly in the form of the airborne Fraunhofer Line Discriminator (FLD).[9,10] Figure 4-B shows the luminescence characteristics of these materials. For these measurements, the surface is illuminated with a narrow band of energy at a given wavelength (called "excitation"), and the surface scanned for the spectral distribution of any luminesced photons. This step is repeated at successive wavelength increments of excitation energy until the spectrum of interest has been covered. The result is a three-dimensional plot of excitation wavelength versus emission wavelength versus intensity, similar to Figure 5-B. In Figure 4-B, the luminescence intensities of the fabrics, vegetation, and soil were plotted for the indicated Fraunhofer lines. Fabrics A and C not only have strong signals as compared to soils and vegetation, but the distributions are different. Thus, they would be easily detectable in a soil/vegetation milieu, as well as distinguishable from each other. When bruised, the vegetation showed a strong luminescence that persisted for hours - indicating a possibility for detecting passage of traffic. When the vegetation is pulverized, the luminescence intensity is further increased.

Figure 5-A, shows the reflectance characteristics of four differently dyed areas of a fabric. Although their composite signal would be distinguishable against a background of vegetation, the contrast would not be necessarily strong, particularly against a mixture of soil and different vegetation types and conditions. On a luminescence basis, the fabric has a signal that greatly exceeds that of vegetation, and which occurs at different wavelengths - making detection a certainty if the areal extent is sufficient (graphs B and C).[11] The signal threshold for airborne detection is 1,500 units, and the fabric's luminescence peak is 81,000 units. In general, vegetal luminescence rarely reaches 20,000 (senesced conditions), and in the healthy state seldom goes above 12,000. The vegetal sample, corn in this case (graph B), has a peak of 11,000. Soils measured to date show very little luminescence. The iso-intensity contour plot, graph C, shows that the luminescence occurs in different wavelength bands.

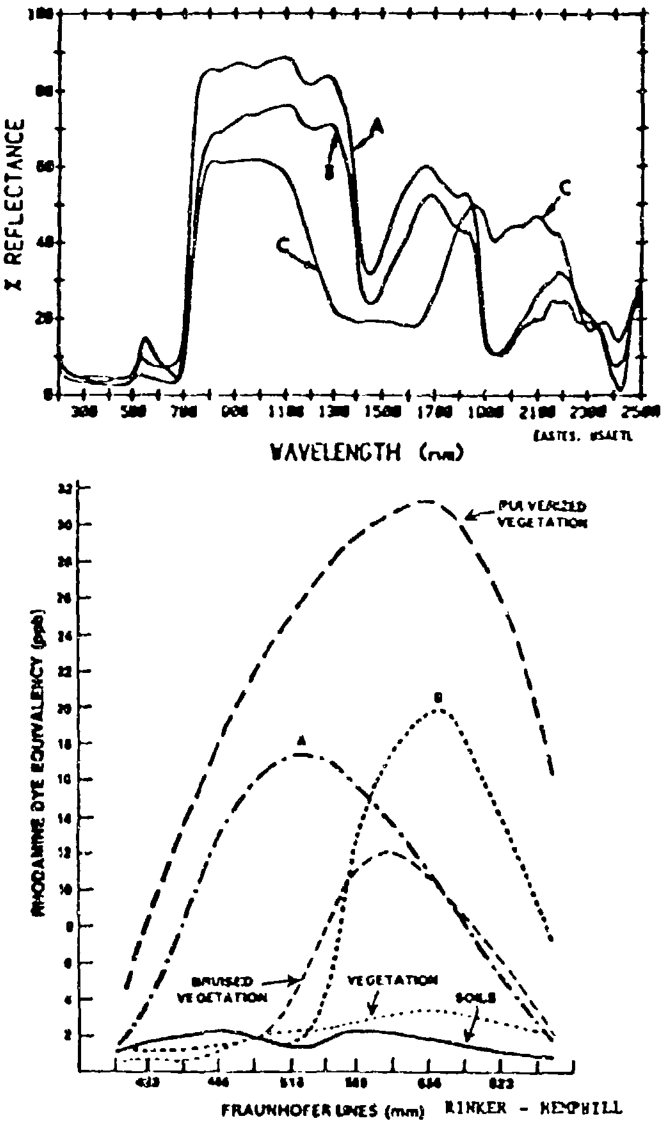

Fig. 4. At the top are spectral reflectances of two fabrics (A and C) and a green leaf (B).[12] Fabric A mimics vegetation, including the water absorption bands, and would be indistinguishable from it. Fabric C is a poor match, and would be easily detected. The lower graph is a plot of luminescence intensity in the Fraunhofer lines of the airborne Fraunhofer Line Discriminator (FLD). Both fabrics show in strong contrast to soils and vegetation (bottom two traces), and also differ significantly from each other. BV indicates the strong signal from bruised vegetation - a signal that persisted for many hours. PV represents the signal from pulverized vegetation.

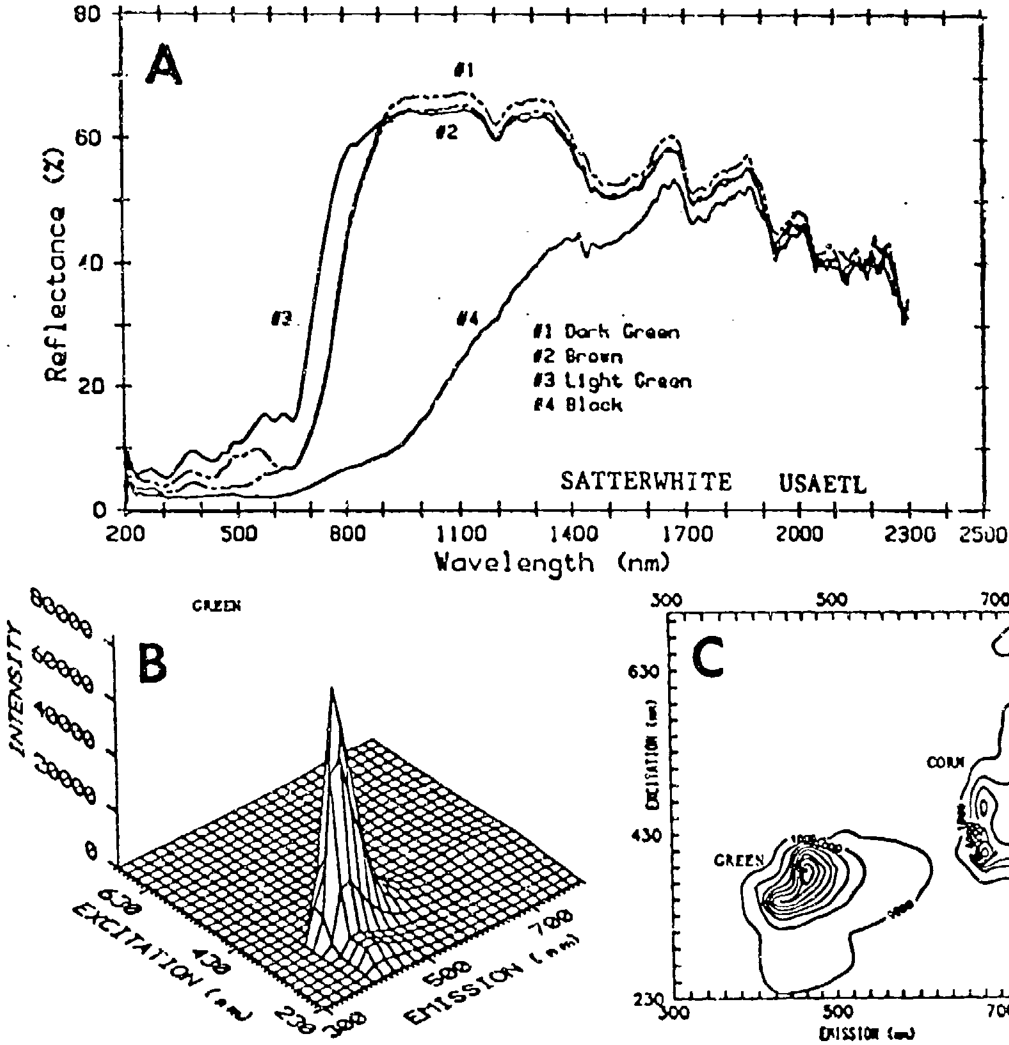

Fig. 5. At the top are the reflectance characteristics of four fabrics. Although distinguishable from vegetation, there would not necessarily be a strong contrast, especially if the background provided a mixture of soils and different types and conditions of vegetation. Graph B is a luminescence plot of the green fabric. Graph C is an iso-intensity plot of the green fabric and of corn, which gives a response typical of healthy herbaceous vegetation. The luminescent intensity of the fabric is 81,000 units. Against the 11,000 intensity units for typical herbaceous vegetation, and the flat response of soils, the fabric with its 81,000 intensity units is easily discernible. Private communication (23 March 1990) suggests a possibility that this high peak is caused by laundry products.

Figure 6 depicts the luminescent characteristics of loblolly pine pollen, whose peak intensities exceed 2,000 units.[13] Implicit in this illustration are a potential application and a potential problem. First, a possible technique for detecting and monitoring airborne pollen loads, i.e., atmospheric quality. Second is a resulting problem - i.e., such an airborne load can reduce contrast, or otherwise interfere with the recording of terrain surface signals.

Although all materials have spectral reflectance characteristics, they do not all have useful luminescence characteristics. Of that portion we have examined, some general statements can be made. With one exception, soils measured to date do not show useful luminescence. About 75 percent of the vegetal samples and 30 percent of the fabrics have detectable and diagnostic luminescence peaks. For healthy turgid vegetation, these peaks fall in the wavelength range between 640 and 800 nm. As vegetation dries out, these peaks decrease in intensity and peaks develop in the wavelength region between 400 and 600 nm. Intensity distributions are related to material type and condition, and the peak intensities can be sorted into fairly distinct groups based on emission wavelengths. As shown in Figure 7, healthy herbaceous vegetation falls into one assemblage, and everything else, e.g., paints, fabrics, pollen, dry vegetation, senesced vegetation, etc., falls in another. Finer distinctions can be made within these groups.

In support of the hyperspectral program, USAETL is developing classification and analytical software; collecting extensive field and laboratory spectral measurements of soils, rocks, vegetation, and man-made materials; and, in cooperation with the U.S. Geological Survey (USGS) group at Flagstaff, AZ, maintaining a series of instrumented test sites that collect around-the-clock measurements of target/background radiation characteristics and concurrent meteorological conditions.[14] The resulting data bases (Table I) support empirical modeling, assisted target recognition, and digital analysis techniques for hyperspectral imagery.

The data bases and the imagery are but the beginnings. Software is being evaluated and/or developed for incorporating the data bases into the computer library; for sample/target classification hierarchies; for display formats, e.g., line spectra, intensity versus wavelength, three-dimensional plots, contour plots, etc.; and for targeting and analytical procedures. There are basic issues to resolve and tasks to be done that involve all the participants in the interagency hyperspectral working group. These include: establishing variances within sets; determination of significant spectral bands (statistical, mathematical, empirical); the importance of absorption band slope changes; atmospheric backout in relation to targets, areas, and conditions; self-calibration of imagery from known data base sets; mixed pixel problem; influence of steady state illumination on luminescence; and testing and validation of existing models.

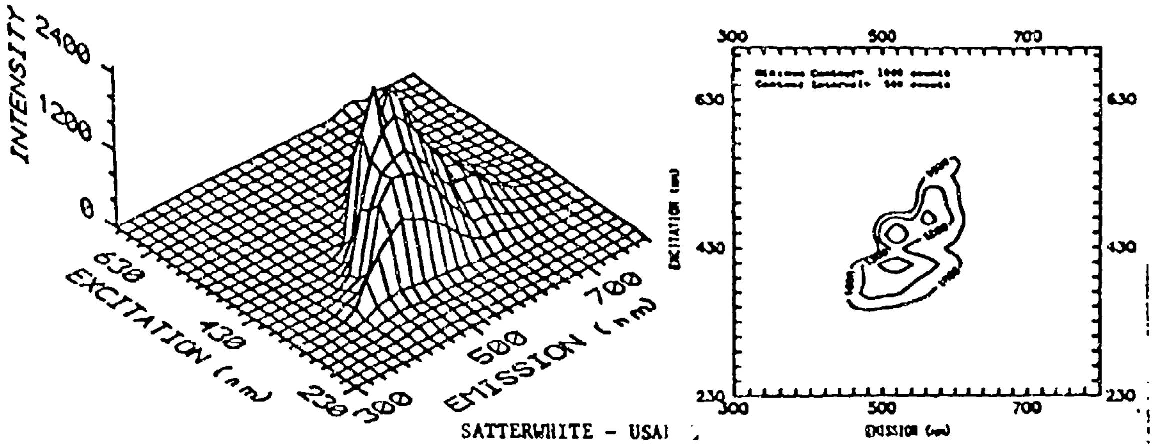

Fig. 6. Luminescence characteristics of loblolly pine pollen. Other pollens also luminesce. Pollen of scrub pine is barely detectable, whereas that of cattails has a signal stronger than that of loblolly pollen. Loblolly pollen, however, consists of very small particle sizes and is readily airborne.

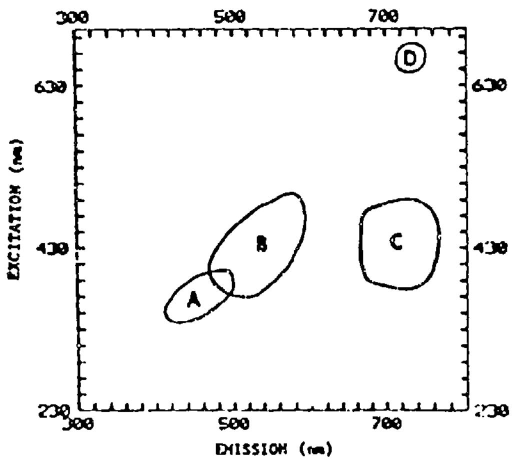

Fig. 7. On a generalized basis, and for those materials that had usable luminescent peaks, the distributions of the peak intensities fall into the indicated areas. With one exception, so far at least, area A contains the fabrics. Area B, which overlaps A to some extent, contains the peaks of pollen, dry vegetation (pine and herbaceous), and senesced vegetation (pine and herbaceous). Area C contains the peaks of healthy vegetation (pine and herbaceous). Area D has a few secondary peaks associated with herbaceous vegetation. The most useful excitance bands are between 330 and 510 nm. The diagnostic emission peaks fall into two groups, 400-600 nm and 660-760 nm, with the latter containing all the healthy herbaceous samples.

Table I. Existing data bases in the USAETL inventory. The temperate data base has eight years of continuous measurements; the subhumid, three and a half years; and the arid, one and a half years. The spectral data bases contain field and laboratory measurements of natural and man-made surfaces, and are collected with an equal or finer spectral resolution than that of the remote sensing hyperspectral systems. Thus, they can be averaged over any selected bandwidth to provide intensity values as they would be in Landsat MSS, TM, TIMS, AVIRIS, etc.

ETL Radiation/Meteorological Data Base - Temperate
ETL/USGS Radiation/Meteorological Data Base - Subhumid
ETL/USGS Radiation/Meteorological Data Base - Arid
ETL Spectral Reflectance Data Base - Solar Radiation (0.4-2.5 micra)
ETL Spectral Reflectance Data Base - Thermal Infrared (2.5-14 micra)
ETL Spectral Luminescence Data Base

The airborne systems are here, e.g., AVIRIS, FLD, and TIMS, needed spectral data bases exist, and enough hyperspectral image sets (solar reflectance, luminescence, thermal IR) have been evaluated by various interest groups to come to some general conclusions. The National Aeronautics and Space Administration (NASA) and JPL have shown the applicability to targeting minerals. USGS, NASA, and the U.S. Department of Agriculture have shown applicability to minerals, petroleum, and vegetation stress. USAETL has shown applicability to military targeting. No technique is a panacea, no system does everything, and the hyperspectral, even in its broadest sense, has its limitations; but, from the standpoint of targeting, the technique has potential beyond any previous remote sensing endeavor.

Targeting refers to the need to detect, and possibly identify, objects and areas of concern to both military and civil needs. Examples include: military hardware and operational units; items such as traffic use, camouflaged positions, and change detection; vegetation typing and vegetation zones altered by aerosols, chemicals, pathogens, and drought; alteration zones or zones of mineralization; areal extent of damage and boundaries associated with flooding, fire, and other natural and man-induced disasters; sediment loads in water; near water surface phytoplankton distribution; and landscape alterations associated with climatic change. Towards these ends a number of interagency cooperative research efforts have been established, ranging from hyperarid and climatic change studies, through camouflage detection and specialized targeting, to disaster evaluation. The latter endeavor, between USAETL and the Canadian National Transportation Safety Board, arose out of the Army's efforts in applying remote sensing techniques to the Gander, Newfoundland airplane crash in December of 1985.[15]

Because of the diversity of requirements within the Army, and the varied activities in its laboratories, the Army has perhaps the largest diverse collection of radiation/meteorological, and spectral reflectance and luminescence data bases available, including associated empirical models and analytical techniques. Although these were developed to support military requirements, they can, without alteration, render direct assistance to critical national and worldwide problems such as narcotics, disaster evaluation, and global climatic change - problems that require all the talents and capabilities that can be brought to bear from both the military and civil domains.

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